Monsoon Variations during the last 171,000 years as Interpreted from terrigenous sediments at ODP Site 723 Western Arabian Sea

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Abstract

The bulk mineralogy of the terrigenous component in 65 samples from ODP Site 723, on the Oman margin, has been determined by x-ray diffraction, using an internal standard method. A detailed mineralogical record of the terrigenous input over the past 171 ky was developed from this data. Previous studies have identified important continental sediment source areas and the minerals derived from each source. Previous studies have also demonstrated that most of this terrigenous material is supplied by the southwest summer monsoon and associated northwest winds. Terrestrial records indicate increased aridity during glacial intervals and increased humidity during interglacial intervals. The mineralogical data generated by this study was used to investigate variations in source area weathering conditions and transport regimes during these climatic changes.

Terrigenous minerals present include smectite, palygorskite, illite, quartz, plagioclase, chlorite, and dolomite, which is consistent with source areas presently supplying sediments to the Arabian Sea. An R-mode principal component analysis identified three mineral assemblages present throughout the past 171 ky: smectite/dolomite (Factor 1), quartz/plagioclase (Factor 2), and palygorskite/illite (Factor 3). Plagioclase, palygorskite, and illite are very susceptible to chemical weathering and therefore Factors 2 and 3 are interpreted to indicate changes in aridity or changes in importance of eolian

transport. Smectite is formed during chemical weathering and dolomite is reduced in grain size by chemical weathering. Factor 1 indicates more humid source conditions and also the importance of source areas directly onshore from Site 723.

Time-series of scores for the three factors indicate both short and long term variability, and do not correlate well to the expected fluctuations in climate predicted by glacial/interglacial intervals. This suggests that local climate shifts were more complex than a simple shift from arid to humid, and that mineral assemblages did not adjust immediately to shifts in climate.

Introduction

Seasonally varying winds over the Arabian Sea (the monsoons), and associated winds directly influence the environments of landmasses bordering the Arabian Sea and may indirectly have a strong influence on world-wide climate. The monsoon is generated by differential heating of the atmosphere over the Arabian Sea and the Indian subcontinent. During the Northern Hemisphere summer this produces high atmospheric pressure over the Arabian Sea and low pressure over India, and the southwest monsoon results. The pressure gradient and the resulting winds are reversed during the Northern Hemisphere winter. Variations in Himalayan topography and the amount of solar radiation over time intervals of tens of thousands to millions of years may have caused variations in monsoon strength and, therefore, affected the paleoclimates of tropical Africa and southern Asia (Prell, Niitsuma, et al., 1989).

The southwest monsoon winds generate ocean currents that cause seasonal upwelling of nutrient-rich waters along the Oman coast. This nutrient-rich water supports an abundance of planktonic organisms that provide abundant skeletal material to the underlying sediments when they die. These processes have a significant effect on the sediments on the Oman margin and the Owen Ridge, a subsurface oceanic mountain range off the coast of Oman (Prell, Niitsuma, et al., 1989). The monsoon winds and associated northwest winds also carry dust to the ocean, and this material settles into the underlying sediments (Prospero, 1981; Spenser et al., 1982). This terrigenous material (i.e., material formed on land) is supplied from the East African Highlands, from Arabia, and, to a lesser extent, from the Indian subcontinent, with distinctive mineral assemblages from each source area. The composition of the terrigenous material supplied from each source area to the modern Arabian Sea reflects present climatic and weathering conditions at that source (Kolla et al., 1981).

As an extension of our knowledge of the modern monsoon, a study of the mineralogy of the terrigenous component of older sediments from this area would provide insight into the history of paleoclimate and weathering conditions of the Arabian Sea and its surrounding landmasses. This project, using sediments recovered from the Oman margin during ODP Leg 117, has developed such a mineralogic record of the terrigenous component of Oman margin sediments for the past 171 ky.

Background

The study described here is an extension of a similar study conducted by Krissek and Clemens (1991), which used sediments recovered from farther offshore on the Owen Ridge. This discussion of the background for such studies, therefore, is derived from the similar presentation by Krissek and Clemens (1991).

Griffin et al. (1968) and Lisitzin (1972) established, on a global scale, relationships between the lithology and the weathering conditions of a continental source area and the composition of the clay mineral assemblage from that source area. Kolla et al. (1976) and Kolla et al. (1981) used these relationships in the western Indian Ocean and the Arabian Sea to interpret clay mineral abundance data. Kolla et al. (1976,1981) concluded from the clay mineral abundance data that:

1- Smectites are predominantly derived from the Deccan Traps of India, enter the Arabian Sea via fluvial discharge, and are transported to the south by surface currents;

2- Illites and chlorites are derived from the Himalayan complex, from the arid regions of Iran-Makran, from alluvial sediments adjacent to the latter region, and from the Thar Desert of India. These minerals are carried to the Arabian Sea by fluvial or eolian processes;

3- Palygorskite is derived from soils of the Arabian Peninsula and Somalia, and is supplied to the Arabian Sea by westerly and southwesterly winds.

Another possible source of smectite (which was not identified by Kolla et al. (1976,1981)), especially considering the location of Site 723, is the ophiolitic rocks present on Masirah Island off the Oman coast (Shackleton and Ries, 1990). Chlorites, dolomite, and detrital carbonates from Oman and palygorskite and smectites from central Arabia may be supplied by northwesterly winds that accompany the summer monsoon (Sirocko and Sarnthein, 1989). Nair et al. (1989) determined from sediment trap data that approximately 80% of the terrigenous sediment in the western Arabian Sea was deposited by eolian transport during the southwest monsoon.

Climatic fluctuations over the course of thousands of years may have affected the mineralogy of sediments derived from these source areas by changing weathering conditions. Increased humidity during interglacials and increased aridity during glacials have been documented (Street and Grove, 1979; van Campo et al., 1982; Prell and van Campo, 1986; and van Campo, 1986) in this area. In addition, mineral assemblage input may have changed because of changes in transport directions; the winter northeast monsoon winds dominated the weaker circulation during glacial periods, while the stronger circulation during interglacials was dominated by transport by the southwest monsoons (van Campo et al., 1982; Prell and van Campo, 1986).

Materials and Methods

This discussion of the materials and methods is derived from the similar presentation by Krissek and Clemens (1991).

This project used sediments recovered from Ocean Drilling Project (O.D.P.) Site 723, which is located on the Oman continental margin at 18 degrees 3 minutes north latitude and 57 degrees 86 minutes east longitude at a depth of 808 meters (Figure 1). Samples from the upper 34 meters of the Site were analyzed for this project. These sediments are contained within Facies I of lithologic Unit I (Shipboard Scientific Party, 1989), which consists of a foraminifer-bearing marly nannofossil ooze and calcareous clayey silt. The sampling interval of the sediments used in this study was 50 cm. Each sample, on average, translates to a time interval of 2.56 ky.

Samples for this study were treated with 30% hydrogen peroxide buffered with ammonium hydroxide to remove organic matter, and with glacial acetic acid to remove biogenic carbonate. Terrigenous residues were freeze dried, and approximately 100 mg of the residue was mixed with 10 mg of boehmite (AlOOH), which served as an internal standard. The mixtures were back-loaded as powders into mounts for X-ray diffraction analysis.

X-ray diffractometry is a standard technique for the mineralogical analysis of geological materials and has been widely applied to the study of terrigenous components of marine sediments. X-ray analyses concentrated on the identification of clay minerals, which are excellent indicators of climate (Carroll, 1974).

All slides were solvated with warm ethylene-glycol vapor for 20 to 24 hours preceding analysis on a Philips diffractometer. Slides were scanned at 1 degree two theta per minute with Ni-filtered CuK-alpha radiation. Data were plotted on a strip chart recorder at 1 degree two theta per inch. The 15-18 angstrom smectite (001), 10.4-10.8 angstrom palygorskite (110), 10 angstrom illite (001), 6.11 angstrom boehmite (020), 4.26 angstrom quartz (100), 4.02 angstrom plagioclase (201), 3.54 angstrom chlorite (004), and 2.89 angstrom dolomite (104) peak areas were measured with a polar planimeter.

Gibbs (1967), Scheidegger and Krissek (1982), and Krissek (1982) have shown that under conditions of uniform grain size and uniform mineral chemical/structural composition, mineral/boehmite peak area ratios may be used to construct calibration curves from which mineral abundances can be calculated. The grain size of the samples used in this study was probably not uniform because bulk samples were used. The lack of uniform grain sizes and the possibility of orientation effects within the pressed powder slides violate the criteria for using calibration curves. Therefore the mineral/boehmite peak area ratios measured for this study cannot be converted to absolute mineral abundances. Although this prevents comparison of the absolute abundances of two or more minerals, variations in the abundance of a single mineral can be described by using the peak area ratios (mineral/boehmite).

Analytical precision was evaluated by comparing peak area ratios for five sets of replicate slides. Precision is estimated as follows (given as absolute mineral/boehmite peak area ratios): +/- 0.35 for smectite, +/- 0.23 for palygorskite, +/- 0.25 for illite, +/- 0.17 for quartz, +/- 0.44 for plagioclase, +/- 1.39 for chlorite, and +/- 0.22 for dolomite. Absolute abundances are accurate at +/- 5% for smectite, +/- 2% for chlorite and illite, and +/- 1% for quartz and plagioclase when determined from mineral/boehmite peak area ratios and calibration curves (Scheidegger and Krissek, 1982; Krissek, 1982). The grain size variations mentioned earlier and the researcher's inexperience are probably responsible for the lower accuracies in this study.

The data from the peak area ratios were examined by R-mode factor analysis for variable-to-variable relationships. The analysis was done using the Principal Components procedure of the SYSTAT 5.0 software package (Wilkinson, 1989). The final factor analysis results were obtained by oblique refinement of a VARIMAX solution. The terminology used here is that of SYSTAT 5.0 (Wilkinson, 1989) and Davis (1986), which labels the coefficients that indicate the importance of each variable on a factor as "loadings," and the coefficients of factor importance to each sample as "scores".

The age of each sample was determined from the age-depth model of Niitsuma et al. (1991), based on oxygen isotope data from Site 723. Ages were established by Niitsuma et al. (1991) who correlated the oxygen isotope record from Hole 723A and 723B to the Specmap (Imbrie et al., 1984) stacked isotope record and work by Prell et al. (1986) and Williams et al. (1988).

Data

Mineral/boehmite peak area ratios are plotted as a function of age in Figure 2 and are tabulated in the Appendix. The variability is significantly greater than the analytical uncertainty in all records except chlorite and plagioclase. The analytical uncertainty is much larger than the changes in the chlorite record, and would mask everything except general trends (if any were present) in the plagioclase record. The other five records generally exhibit a small increase and decrease between approximately 0 and 120 thousand years before present(KyBP) and a well-defined increase from approximately 120 KyBP to the end of the record at 171 KyBP.

Discussion

Smectite, palygorskite, illite, quartz, plagioclase feldspar, chlorite, and dolomite are the important terrigenous minerals at Site 723. All of these minerals have been identified as important constituents in studies of Holocene and modern Arabian Sea sediments and aerosols (Sirocko and Sarnthein, 1989: Debrabant et al., 1991; Chester et al., 1985; Kolla et al., 1976, 1981). Because of the extended time span represented by the sediments of this study (171 ky), these sediments provide an opportunity to evaluate changing conditions in the source areas that contribute sediments to the Oman margin.

Mineral associations have been identified by performing an R-mode principal component analysis, with oblique refinement of a Varimax solution (Leland, 1989). As in Krissek and Clemens (1991), this application assumes that all relevant matrix variance has been included when the sum of the proportionate contributions of the eigenvalues exceeds 0.75. For the Site 723 data, three factors are required to exceed that value. The contribution of each factor to explaining the original variance, and the contribution of each to the variance after oblique refinement of the Varimax solution are given in Table 1. Table 2 indicates the loading (importance) of each variable (mineral) on each of the three factors.

Krissek and Clemens (1991) noted that temporal variations in the importance of factors (assemblages of minerals) could be interpreted to emphasize either of two effects. First, temporal variations could indicate changes in the importance of specific source areas caused by changes in sediment transport paths. This would be true as long as the characteristics of the mineral assemblage derived from a source stayed constant over time, especially through glacial/interglacial fluctuations. Second, temporal variations could indicate climatically induced changes in the mineralogy of sediments derived from less precisely located source areas, assuming that the monsoon has dominated sediment input over time. In their study of sediments from the Owen Ridge, Krissek and Clemens (1991) chose the second interpretation. The three reasons given for this choice are (1) continental climates are known to have changed significantly during glacial/interglacial fluctuations (Street and Grove, 1979; van Campo et al., 1982; Prell and van Campo, 1986), which would suggest changes in the mineral assemblages derived from continental source areas; (2) the importance of the monsoon throughout the past million years has been recognized in marine faunal indicators of monsoon-induced upwelling (Prell and Curry, 1981; Prell 1984) and in eolian grain size and MAR (mass accumulation rate) records on the Owen Ridge (Clemens and Prell, 1990); and (3) potential source areas are extensive, therefore the expected changes in wind paths from glacials to interglacials would not have changed source areas enough to explain the large variations observed in the mineralogy.

For a site on the continental margin, such as Site 723, a more balanced consideration of the effects of changing both climate and transport pathway is more appropriate. Because sediment is supplied from relatively nearby continental sources, temporal variations in the importance of a factor may reflect changes in the importance of a specific continental source. But, for mineral assemblages supplied from relatively distant sources by eolian transport, the effects of climatically controlled changes in weathering conditions are probably more important (for all three reasons stated above). Mineral assemblages controlled by climatic conditions would be more likely to exhibit the effects of glacial/interglacial fluctuation, although changes in transport paths could also respond to glacial/interglacial variations.

In this context, the factors may be interpreted as follows:

1- Factor 1 is dominated by high positive loadings for smectite and dolomite and intermediate loadings on illite and quartz. Therefore, Factor 1 is an indicator of an association of smectite and dolomite, which are both associated to a lesser extent with illite and quartz. Smectite is created by moderate weathering of source lithologies, especially basic to intermediate igneous rocks (Velde, 1985). Sources for smectite include the Deccan Trap basalts, the Arabian Peninsula, and East Africa (Kolla et al., 1981). Dolomite grain size is reduced by moderate weathering, but the mineral is not resistant to heavy weathering (Dixon and Weed, 1977). Dolomite source areas are best exposed on the Arabian Peninsula and in Oman (Sirocko and Sarnthein, 1989). Figure 3 illustrates the proximity of smectite source areas (the rocks on Masirah Island, at Ras Madrakah, and throughout the Oman Mountains) and dolomite source areas (Huqf-Haushi area) (Wright, et al., 1990; Shackleton and Ries, 1990) to Site 723. The proximity of these source areas to Site 723 suggests that a majority of these two minerals is derived from the Arabian Peninsula. Therefore, variations in the importance of this factor probably reflect changes in the importance of the source area due to changes in transport path or amount of runoff. A minor amount of the smectite present may reflect increased weathering in the source area caused by climatic changes, and therefore some variation could be interpreted as a record of climatic change.

Factor 2 is dominated by high positive loadings on quartz and plagioclase. Quartz is readily produced from a variety of source areas under a variety of weathering conditions (Krissek and Clemens, 1991). Plagioclase feldspar is unstable except under minimal weathering conditions. Because of the presence of plagioclase, variations in this factor may reflect limited amounts of weathering and, therefore, a source area experiencing an arid climate. The low estimates of plagioclase reproducibility prevent interpretations of climatic changes based only on plagioclase from being considered seriously. Therefore, Factor 2 is dominated by quartz, which is not a distinctive climatic indicator.

Factor 3 is dominated by high positive loadings on palygorskite and illite. Both palygorskite and illite are highly susceptible to chemical weathering (Dixon and Weed, 1977; Blatt et al. 1980; Velde, 1985) and, therefore, denote a source area with an arid climate. The major source areas of palygorskite to the Arabian Sea are the Arabian Peninsula and East Africa. The major source areas of illite to the Arabian Sea are Iran-Makran, the Arabian Peninsula, and Somalia (East Africa) (Kolla et al., 1981; Sirocko and

Sarnthein, 1989). Because of the association of these two minerals, the source area is interpreted to be the Arabian Peninsula and/or East Africa.

In summary, the mineral assemblages of Factor 1 and 2 probably reflect the proximity of source areas on the Arabian Peninsula and record the variations in the importance of input from these sources. Some variation may record enhanced chemical weathering effects for Factor 1. Factor 2 could indicate fluvial input or eolian input (by the northwest winds) of quartz. The plagioclase record could indicate arid conditions and limited chemical weathering. The assemblage of Factor 3 records arid conditions and limited chemical weathering in a less well defined source area.

The time series of factor scores (Figure 4 and Appendix) can be used to identify temporal variations in the relative importance of each mineral assemblage. Each time-series exhibits variability ranging from short term (approximately 20 k.y.or less) to long term (approximately 100 to 120 k.y.) The short term variability is present in all three time-series, whereas the long term variability is best illustrated in Factor 1.

As described by Krissek and Clemens (1991), detailed interpretation of source area paleoclimates from the factor scores is complicated by the predominance of short term variability in all three time-series. This short term variability is present in part because erosional products do not respond immediately to changes in climate. Therefore, the mineral assemblages deposited at a particular time combine the weathering effects of previous and contemporaneous climates. This lag effect is evident by examining the factor scores for the last glacial maximum (isotopic stage 2, centered at approximately 18 ka; Imbrie et al., 1984) and the last interglacial (isotopic stage 5.5, centered at approximately 125 ka; Imbrie et al., 1984). These data are summarized in Table 3. Pollen assemblages (van Campo et al., 1982; Prell and van Campo, 1986) indicate that the last glacial maximum was arid but the 18 ka sample has low scores for the two arid factors. Pollen assemblages indicate that the last interglacial was humid but the humid factor (Factor 1) has a low value in that sample. Factor 2 has a large negative score for the interglacial sample which agrees with results expected for an arid factor during a humid interglacial. The more reliable arid factor (Factor 3), however, has a high positive value for the interglacial sample which is the opposite of the results expected from the pollen record of interglacial humidity.

The dust component of samples is usually considered an indicator of aridity/humidity instead of wind strength. This is because the presence or absence of plant growth, which is controlled by aridity/humidity, has more control over the amount of terrestrial sediment transported than the wind strength. Pollen data shows that even during humid interglacials, arid environments persisted (van Campo et al., 1982). If an arid environment was persistent than transport from that area would show variation due to changes in wind strength. The persistence of arid environments would allow for the continued availability of palygorskite in some areas. If Factor 3 is considered an indicator of wind strength rather than aridity/humidity, its factor scores for the last glacial and interglacial maximums agree with expected results. For Factor 3, the glacial maximum, with its lower wind speeds, has a low factor score, and the interglacial maximum, with its higher wind speeds, has a high factor score.

This lack of correlation with results dictated by expected aridity or humidity could be caused partially by the interpretation that changes in Factors 1 and 2 are controlled mostly by changes in transport path. In general though, these results indicate that the mineral assemblages deposited on the Oman Margin were influenced by a range of controls and, therefore, do not directly act as a record of source area paleoclimates.

A comparison of the factors at Site 723 and those reported by Krissek and Clemens (1991) at Site 722 reveals several differences. Factor 1 at Site 722 is dominated by quartz and chlorite, which is interpreted as indicating arid source regions. Factor 2 is dominated by kaolinite, plagioclase, and illite; and Factor 4 is dominated by palygorskite and, to a lesser extent, dolomite; both factors are also interpreted as indicating arid source regions.

Factor 3 of Site 722 is dominated by smectite, which is interpreted as indicating humid source areas. At Site 722, palygorskite (Factor 4) exhibits an obvious 100 ky cycle in its time-series of factor scores. Factor 3 at Site 723, which is also dominated by palygorskite (and illite), has no obvious 100 ky cycle (although an approximately 20 ky long cycle can be identified). A 100 ky cycle may be identifiable in the palygorskite record at Site 723 if the record was extended beyond 171 ka.

These differences in the sediment records at the two sites are probably caused by the differences in their distance from shore. Because Site 723 is directly offshore from possible source areas, Factor 1 and Factor 2 reflect mineral assemblages derived from those adjacent source areas. The factors at Site 722, because of its distance from shore, are dominated by mineral assemblages provided by eolian input from more distant source areas.

Summary

Smectite, palygorskite, illite, quartz, plagioclase, chlorite, and dolomite are the dominant terrigenous components deposited on the Oman Margin. This mineralogy is consistent with the composition of the source areas currently supplying sediments to the Arabian Sea. Significant climatic changes have occurred in the past 171 thousand years, therefore the mineralogy of sediments supplied from the source areas may have changed through time. Principal component analysis of the mineral abundances has identified three mineral assemblages present at Site 723: a smectite/dolomite assemblage (Factor 1), a quartz/plagioclase assemblage (Factor 2), and a palygorskite/illite assemblage (Factor 3). The close proximity of possible source areas for smectite and dolomite suggests that changes in supply of this assemblage explain much of its variation over time. Some changes in Factor 1 may record the episodic establishment of a relatively humid source area. Plagioclase, palygorskite, and illite are all susceptible to chemical weathering, suggesting that both Factor 2 and Factor 3 reflect arid continental source conditions. Increased importance of Factor 3 may reflect an increase in wind velocity in the region.

Pollen data indicate that continental areas around the Arabian Sea were more humid during interglacial intervals and more arid during glacials. Time-series of scores for the arid and humid factors do not correspond well to this record of climatic change. Instead, Factor 3 (an arid factor) may be a better indicator of wind speed than aridity, because the palygorskite-forming environments of Factor 3 appear to be insensitive to glacially driven aridity. The explanation for this poor correlation is that local environments are more complex than simple transitions between arid glacials and humid interglacials and that each assemblage adjusts to climatic change at a different rate (Krissek and Clemens, 1991).

Future work should attempt to increase the length of the record to obtain better resolution of the cycles that are present. Also, spectral analysis of the factor score records might separate paleoclimatically controlled signals from signals created by other effects. Spectral analysis would therefore eliminate lag effects created by different temporal response to changes in climate / weathering.

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References

Blatt, H., Middleton, G. V., and Murray, R., 1980. Origin of Sedimentary Rocks (2nd ed.): Ney Jersey (Printice-Hall).

Carroll, D., 1974. Clay Minerals: A guide to their X-ray Identification. Geological Society of America Special Paper 126, Boulder, Co.

Chester, R., Sharples, E. J., and Sanders, G. S., 1985. "The concentration of particulate aluminum and clay minerals in aerosols from the northern Arabian Sea." J. Sediment. Petrol., 55:37-41.

Clemens, S.C., and Prell, W.L., 1990. "Late Pleistocene variability of Arabian Sea summer monsoon winds and continental aridity: eolian records from the lithogenic component of deep-sea sediments." Paleoceanography, 5:109-145.

Davis, J.C., 1986. Statistics and Data Analysis in Geology (2nd ed.): New York (Wiley).

Debrabant, P., Krissek, L., Bouquillon, A., and Chamley, H., 1991. "Clay mineralogy of Neogene sediments of the Western Arabian Sea: mineral abundances and paleoenvironmental implications." In Prell, W.C., Niitsuma, N., Emeis, K.C. et al., Proceedings ODP, Scientific Results, 117: College Station, TX.

Dixon, J.B., and Weed, S.B., 1977. Minerals in Soil Environments: Madison, WI (Soil Sci. Soc. of Am.).

Gibbs, R.J., 1967. "Quantitative X-ray diffraction analysis using clay mineral standards extracted from the samples to be analyzed." Clay Min., 7:79-90.

Griffin, J., Windom, H., and Goldberg, E.D., 1968. "The distribution of clay minerals in the world ocean." Deep-Sea Res., 15:433-459.

Imbrie, J., Hays, J.D., Martinson, D.G., McIntyre, A., Mix, A.C., Morley, J.J., Pisias, N.G., Prell, W.L., and Shackleton, N.J., 1984. "The orbital theory of Pleistocene climate: support from a revised chronology of the marine oxygen isotopic record." In Berger, A., Imbrie, J., Hays, J., Kukla, G., and Saltzman, B. (Eds.), Milankovitch and Climate (Pt. 1): Dordrecht (D. Reidel), 269-305.

Kolla, V., Henderson, L., and Biscaye, P.E., 1976. "Clay mineralogy and sedimentation in the western Indian ocean." Deep-Sea Res. Oceanogr. Abstr., 23:949-961.

Kolla, V., Kostecki, J.A., Robinson, F., Biscaye, P.E., and Ray, P.K., 1981. "Distribution and origins of clay minerals and quartz in surface sediments of the Arabian Sea." J. Sediment. Petrol., 51:563-569.

Krissek, L.A., 1982. Sources, dispersal, and contributions of fine-grained terrigenous sediments on the Oregon and Washington continental slope [Ph.D. dissert.]. Oregon State Univ., Corvallis.

Krissek, L., and Clemens, S., 1991. "Mineralogic variations in a Pleistocene high-resolution eolian record from the Owen Ridge, Western Arabian Sea (Site 722):Implications for sediment sources, dispersal, and monsoon history." In Prell, W.C., Niitsume, N., Emeis, K.C., et al., Proceedings ODP, Scientific Results, 117: College Station, TX.

Lisitzin, A.P., 1972. Sedimentation in the World Ocean, with Emphasis on the Nature, Distribution, and Behavior of Marine Suspensions. Soc. Econ. Paleontol. Mineral. Spec. Pub., 17.

Nair, R.R., Ittekkok, V., Manganini, S.J., Ramaswamy, V., Haake, B., Degens, E.T., Desai, B.N., and Honjo, S., 1989. "Increased particle flux to the deep ocean related to monsoon." Nature, 338: 749-751.

Niitsuma, N., Oba, T., and Okada, M., 1991. "Oxygen and carbon isotope stratigraphy at Site 723, Oman Margin." In Prell, W.C., Niitsuma, N., Emeis, K.C., et al., Proceedings ODP, Scientific Results, 117 College Station, TX.

Prell, W.L., 1984. "Monsoonal climate of the Arabian Sea during the late Quaternary: a response to changing solar radiation." In Berger, A.L., Imbrie, J., Hays, J., Kukla, G., and Saltzman, B. (Eds.). Milankovitch and Climate (Pt. 1): Dordrecht (D. Reidel), 349-366.

Prell, W.L., and Curry, W.B., 1981. "Faunal and isotopic indices of monsoonal upwelling: western Arabian Sea." Oceanol. Acta. 4:91-98.

Prell, W.L., Imbrie, J., Martinson, D.G., Marley, J.J., Pisias, N.G., Shakleton, N.J., and Streeter, H.F., 1986. "Graphic correlation of oxygen isotope stratigraphy application to the late Quaternary." Paleoceanography, 1:137-162.

Prell, W.L., Niitsuma, N., et al., 1989. "Introduction, Background, and Major Objectives for ODP Leg 117 (Western Arabian Sea) in search of Ancient Monsoons." Proc. ODP, Init. Repts. 117: College Station, TX.

Prell, W.L., and van Campo, E., 1986. "Coherent response of Arabian Sea upwelling and pollen transport to late Quaternary monsoonal winds." Nature, 323:526-528.

Prospero, J.M., 1981. "Arid regions as sources of mineral aerosols in the marine atmosphere." In Troy, L.P.(Ed.) Desert Dust: Origin, Characteristics, and effects on Man. G.S.A. Special Paper, pp. 71-86.

Scheidegger, K.F., and Krissek, L.A., 1982. "Dispersal and deposition of eolian and fluvial sediments off Peru and northern Chile." Geol. Soc. Am. Bull., 93:150-162.

Shackleton, R.M. and Ries, A.C. 1990. "Tectonics of the Masirah Fault Zone and eastern Oman." In Robertson, A.H.F., Searle, M.P. and Ries, A.C. (Eds.). The Geology and Tectonics of the Oman Region. Geological Society of London Special Publication no. 49, London, pp 715-724.

Shipboard Scientific Party, 1989. Site 723. In Prell, W.L., Niitsuma, N., et al., Proc. ODP, Init. Repts., 117: College Station, TX (Ocean Drilling Program).

Sirocko, F., and Sarnthein, M., 1989. "Wind-borne deposits in the northwest Indian Ocean: record of Holocene sediments versus modern satellite data." In Leinen, M., and Sarnthein, M. (Eds.), Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport. NATO ASI ser., 282:401-433.

Spencer, D., Broecker, W.S., Craig, H., and Reis, R.F., 1982. GEOSECS Indian Ocean Expedition, Sections and Profiles, 6, IDOE, National Science Foundation.

Street, F.A., and Grove, A.T., 1979. "Global maps of lake -level fluctuations since 30,000 yr B.P." Quat. Res., 12:83-118.

van Campo, E., 1986. "Monsoon fluctuations in two 20,000-yr B.P. oxygen-isotope/pollen records off southwest India." Quat. Res., 26:376-388.

van Campo, E., Duplessy, J.C., and Rossignol-Strick, M., 1982. "Climatic conditions deduced from a 150-k.y. oxygen isotope-pollen record form the Arabian Sea. Nature, 296:56-59.

Velde, B., 1985. Clay Minerals: A Physico-Chemical Explanation of Their Occurrence: Amsterdam (Elsevier).

Wilkinson, L., 1989. Systat: The System for Statistics Evanston, IL: Systat Inc.

Williams, D.F., Thunnell, R.C., Tappa, E., Rio, D., and Raffi, I., 1988. "Chronology of the Pleistocene oxygen-isotope record: 0 - 1.88 m.y. B.P." Palaeogeogr., Paleoclimatol., Palaeoecol., 64: 221-240.

Wright, V.P., Ries, A.C., and Munn, S.G., 1990. "Intraplatformal basin-fill deposits from the Infracambrian Huqf Group, east Central Oman." In Robertson, A.H.F., Searle, M.P., and Ries, A.C. (Eds.). The Geology and Tectonics of the Oman Region. Geological Society of London Special Publication no. 49, London, pp. 601-616.

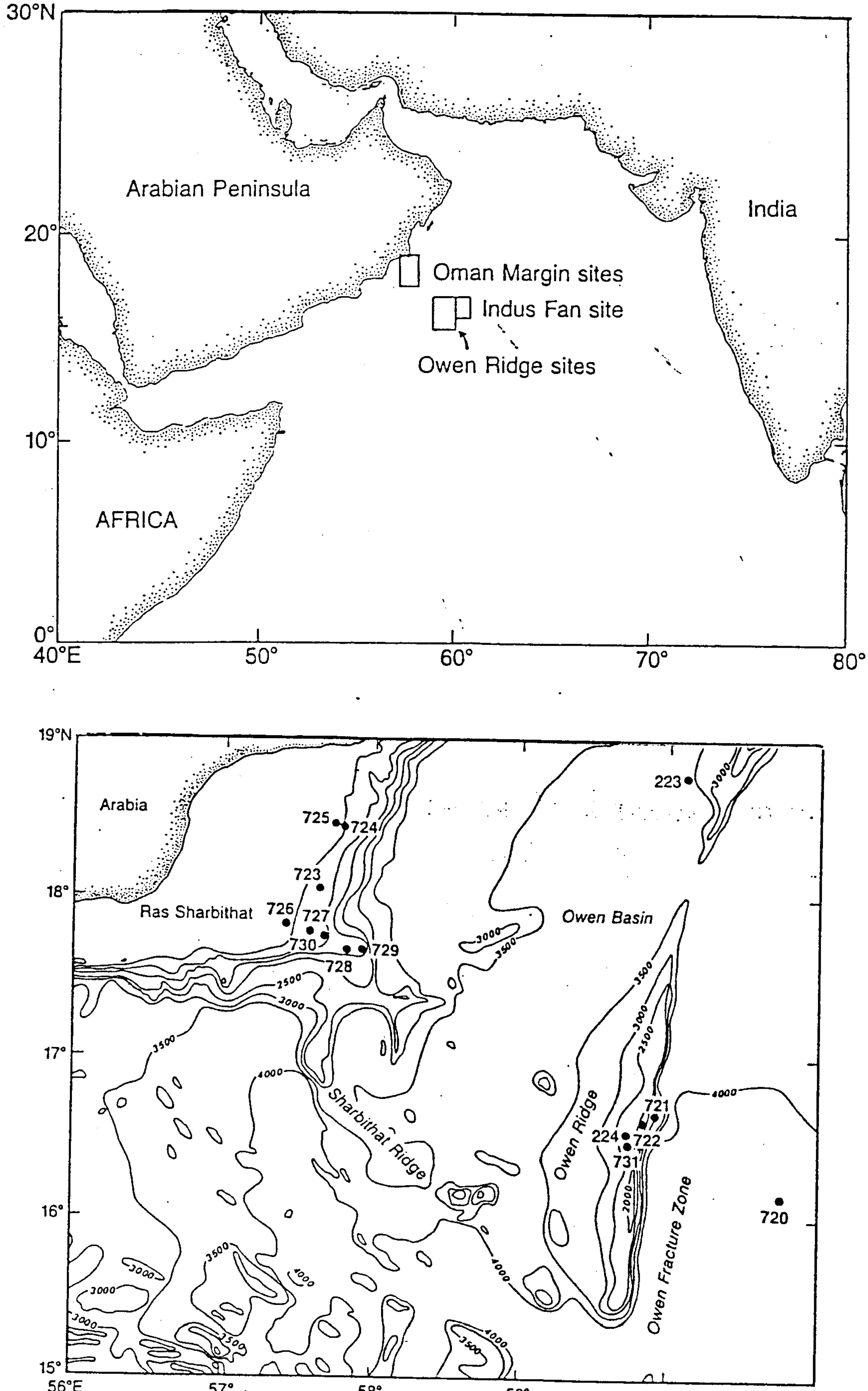

Figure 1. Location map of ODP Leg 117 sites in the Arabian Sea including Site 723 on the Oman Margin (From Prell, Niitsuma, et al., 1989)

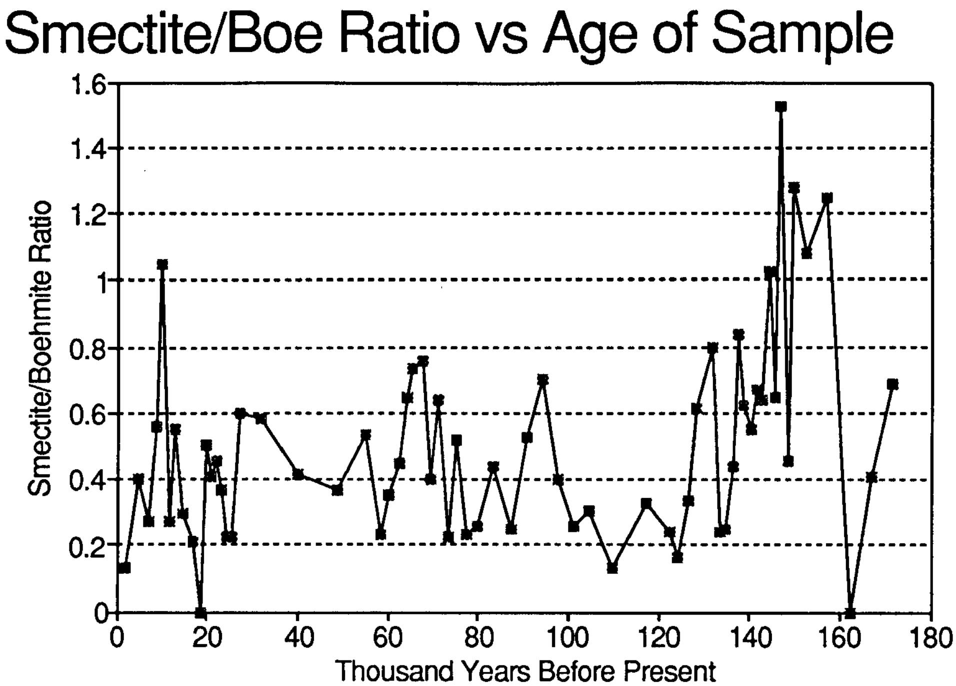

Figure 2a. Mineral abundance data (smectite/boehmite peak area ratios) at ODP Site 723, plotted as a function of age.

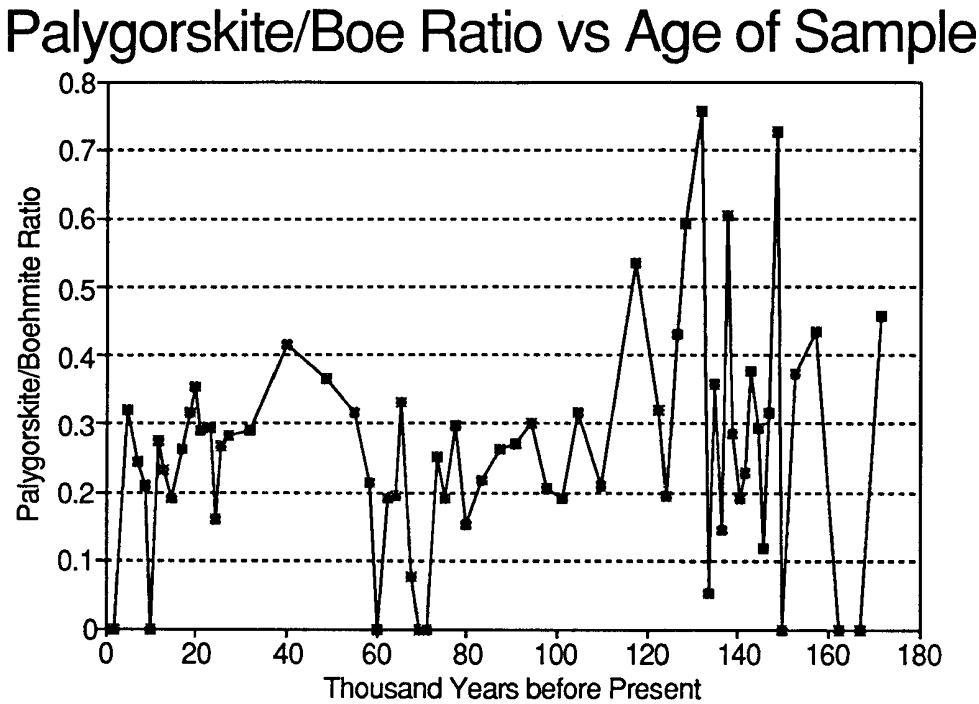

Figure 2b. Mineral abundance data (palygorskite/ boehmite peak area ratios) at ODP Site 723, plotted as a function of age.

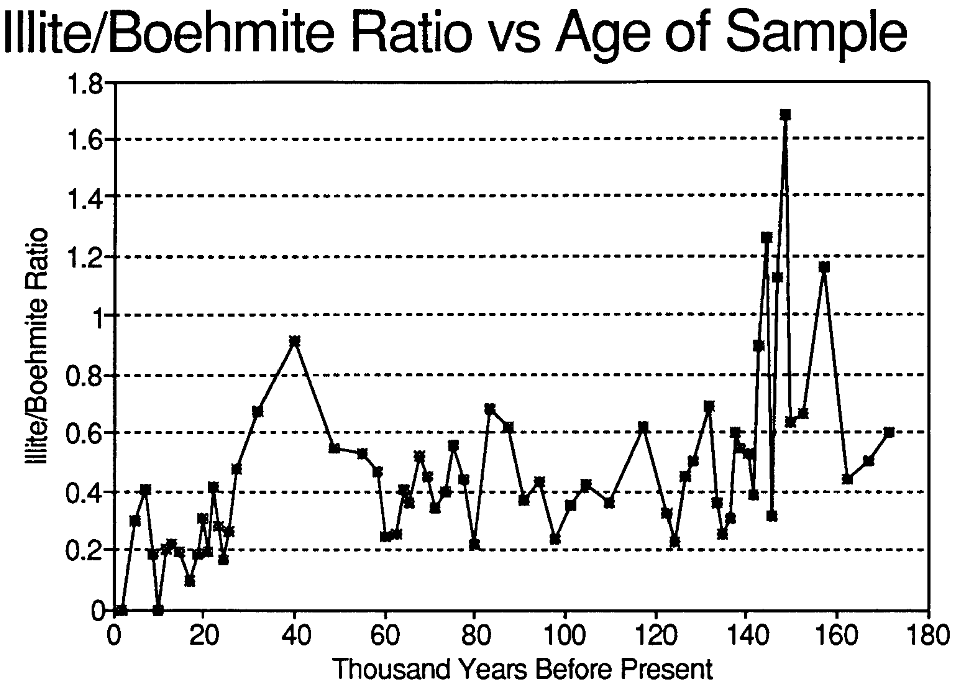

Figure 2c. Mineral abundance data (illite/boehmite peak area ratios) at ODP Site 723, plotted as a function of age.

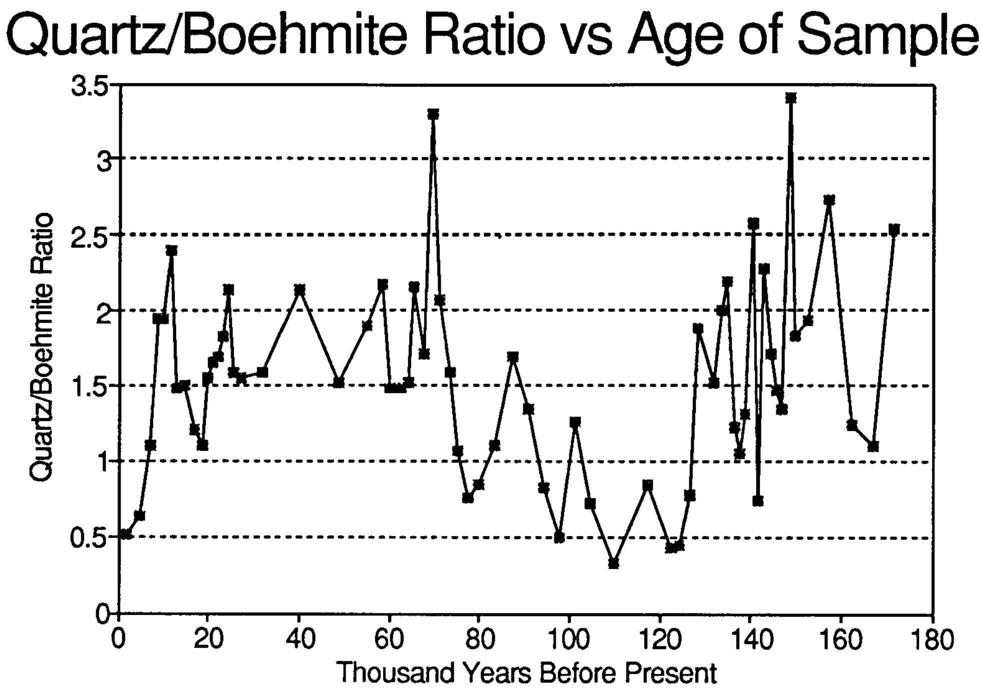

Figure 2d. Mineral abundance data (quartz/boehmite peak area ratios) at ODP Site 723, plotted as a function of age.

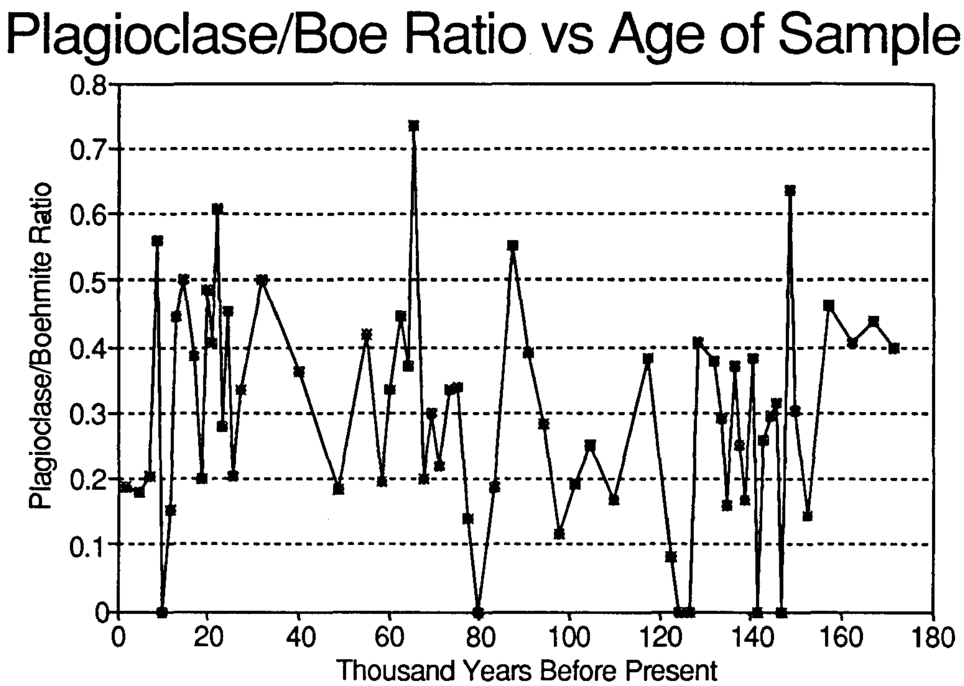

Figure 2e. Mineral abundance data (plagioclase/ boehmite peak area ratios) at ODP Site 723, plotted as a function of age.

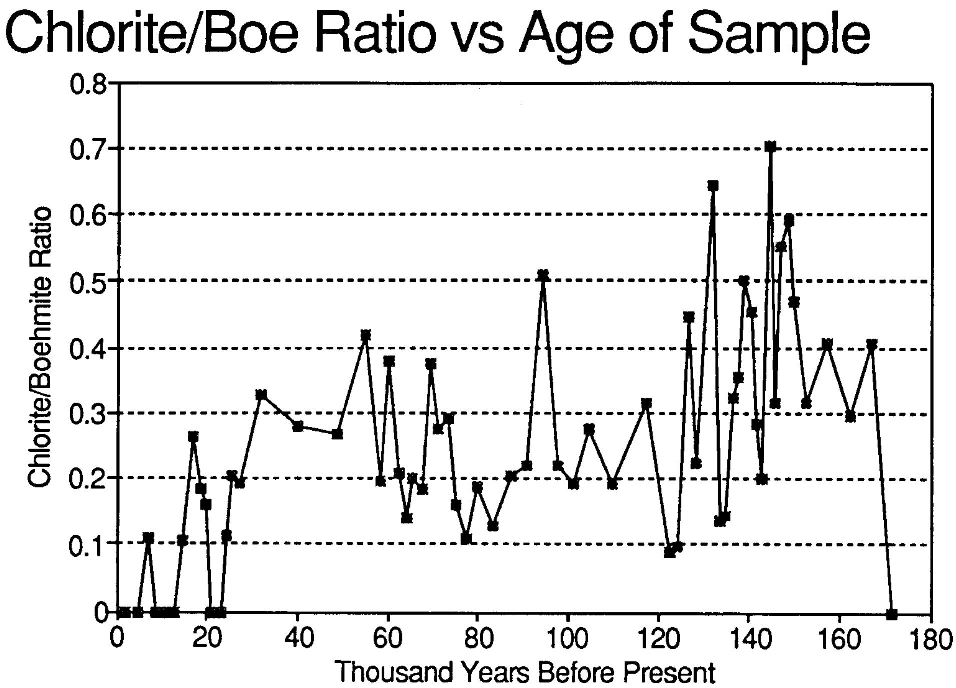

Figure 2f. Mineral abundance data (chlorite/boehmite peak area ratios) at ODP Site 723, plotted as a function of age.

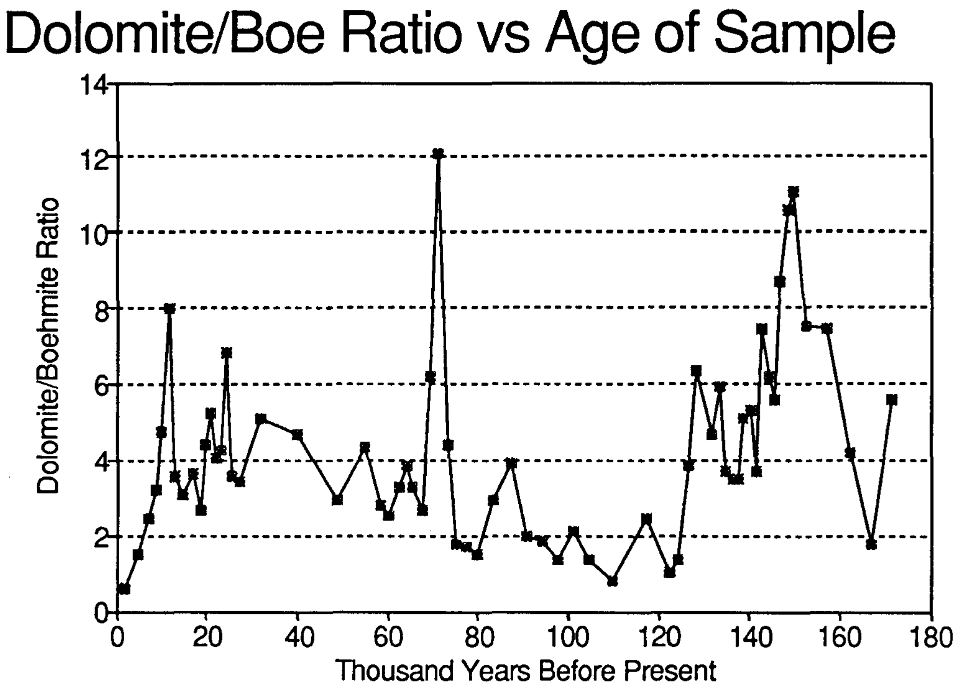

Figure 2g. Mineral abundance data (dolomite/boehmite peak area ratios) at ODP Site 723, plotted as a function of age.

Table 1.
Proportions of data variance explained by first three factors after initial R-mode analysis and following the oblique/VARIMAX solution refinement.

Proportion (%)	Factor 1	Factor 2	Factor 3
Of Original Variance	43	19	15
Of Variance after oblique/varimax	32	23	23

Table 2.
Loadings of each variable on each of the three factors extracted by R-mode factor analysis from the mineral/ boehmite peak area ratio data. Factor 1 is dominated by smectite and dolomite, Factor 2 is dominated by quartz and plagioclase, and Factor 3 is dominated by palygorskite and illite.

	Factor Loadings		
Variable	Factor 1	Factor 2	Factor 3
Smectite	0.81	-0.04	0.15
Palygorskite	-0.03	0.16	0.87
Illite	0.58	0.16	0.68
Quartz	0.49	0.78	-0.04
Plagioclase	-0.13	0.84	0.22
?Chlorite?	0.58	-0.15	0.55
Dolomite	0.80	0.43	-0.03

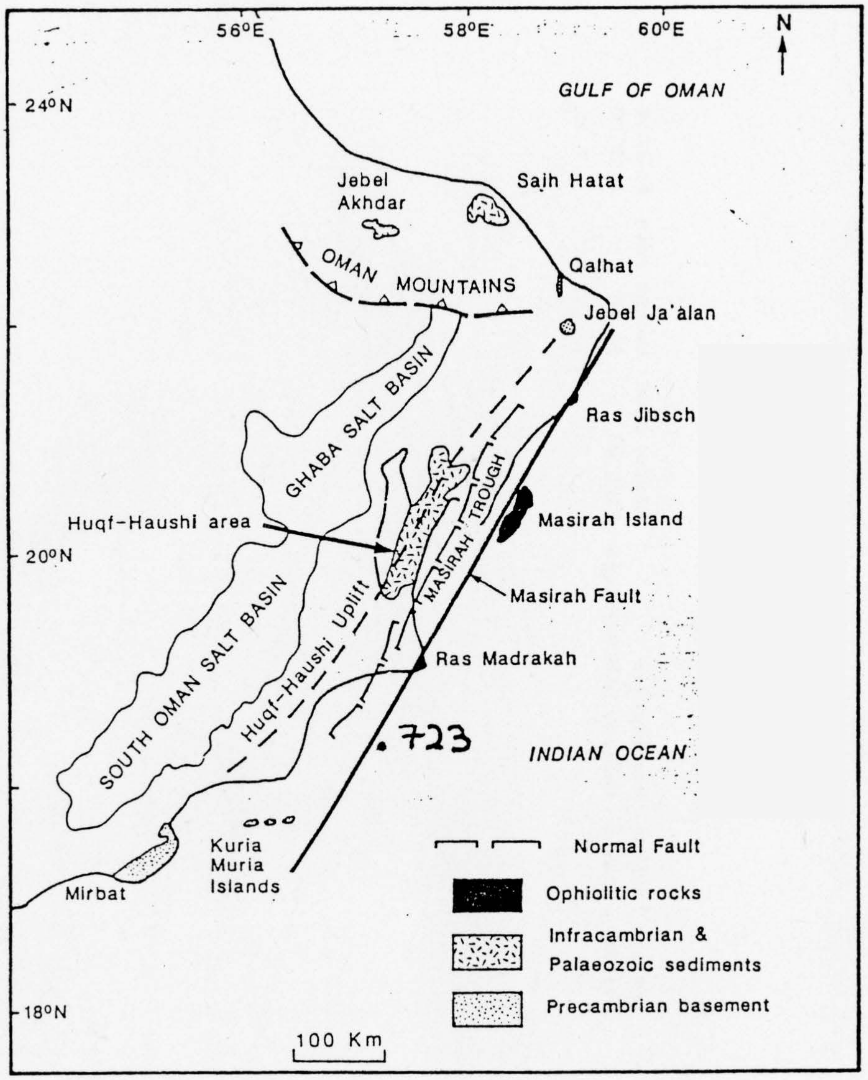

Figure 3. Map of the Oman Margin region and approximate location of Site 723. Ophiolitic rocks (and possible sources of smectite) are located in the Oman Mountains, on Masirah Island, and at Ras Madrakah. Sources of dolomite are located in the Huqf-Haushi area and throughout the sabkha (From Shackleton and Reis, 1990)

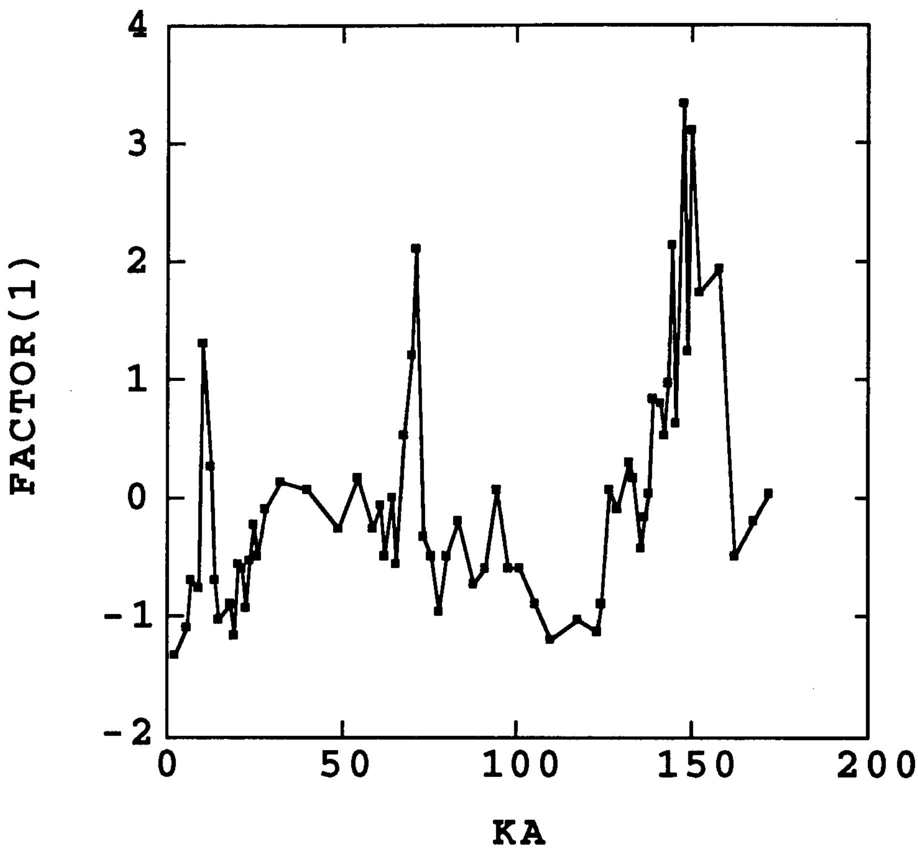

Figure 4a. Scores for Factor 1 at Site 723 defined by principal component analysis and an oblique/Varimax solution refinement. Loadings of each variable on each factor are listed in Table 2. Factor 1 is dominated by smectite and dolomite.

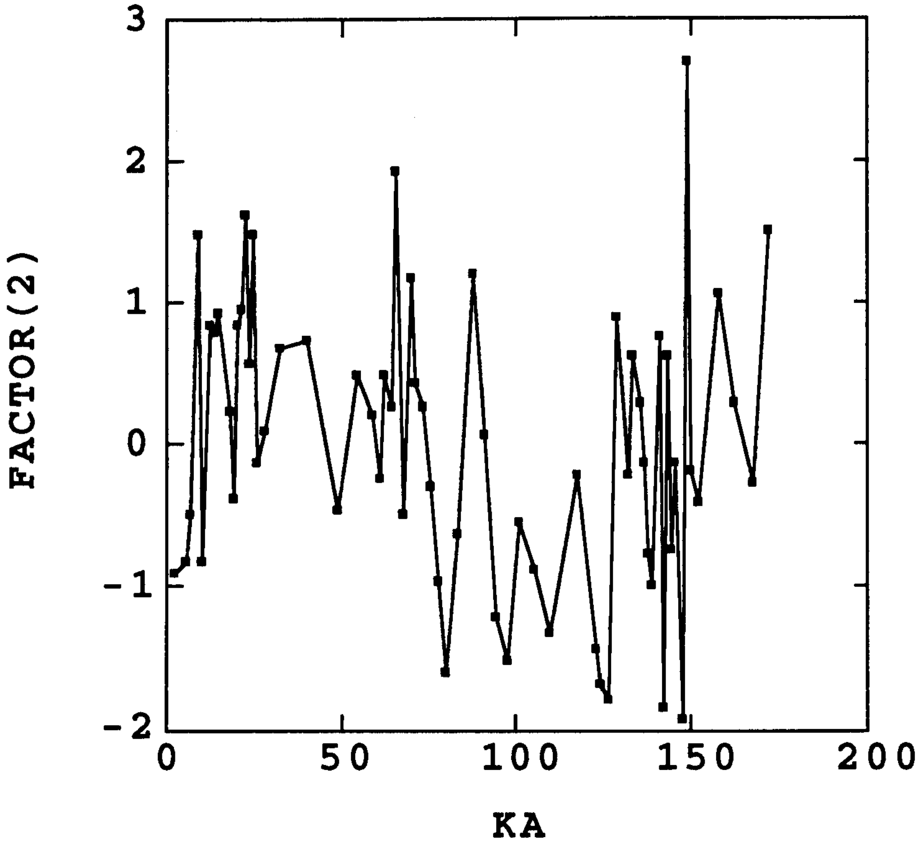

Figure 4b. Scores for Factor 2 at Site 723 defined by principal component analysis and an oblique/Varimax solution refinement. Loadings of each variable on each factor are listed in Table 2. Factor 2 is dominated by quartz and plagioclase(?).

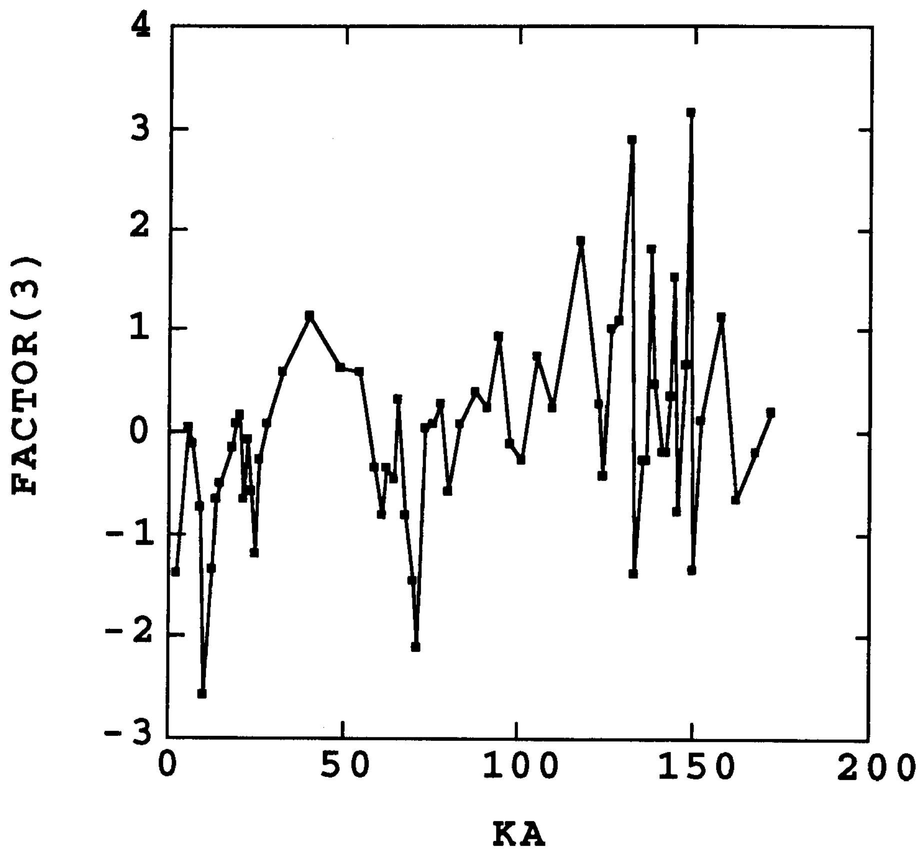

Figure 4c. Scores for Factor 3 at Site 723 defined by principal component analysis and an oblique/Varimax solution refinement. Loadings of each variable on each factor are listed in Table 2. Factor 3 is dominated by palygorskite and illite.

Table 3

Factor scores for samples from the last glacial maximum (18ka) and the last interglacial (125ka)

Sample Age (ka)	Factor Scores		
	Factor 1	Factor 2	Factor 3
18	-1.155	-0.382	0.068
125	0.066	-1.786	1.014

Data for Samples from Hole 723B

MBSF	Ky	Smectite	Palygor	Illite	Quartz	Plagio	Chlorite	Dolomite	Factor 1	Factor 2	Factor 3
0.35	2.14	0.13	0.00	0.00	0.52	0.19	0.00	0.58	-1.317	-0.914	-1.388
0.85	5.05	0.40	0.32	0.29	0.64	0.18	0.00	1.50	-1.073	-0.835	0.041
1.35	7.09	0.27	0.24	0.41	1.09	0.20	0.11	2.47	-0.701	-0.491	-0.112
1.85	8.69	0.56	0.21	0.19	1.95	0.56	0.00	3.23	-0.757	1.484	-0.741
2.35	10.3	1.05	0.00	0.00	1.94	0.00	0.00	4.73	1.314	-0.814	-2.59
2.85	11.9	0.28	0.28	0.20	2.40	0.15	0.00	8.03	0.281	0.838	-1.347
3.35	13.14	0.55	0.23	0.21	1.48	0.45	0.00	3.55	-0.673	0.78	-0.634
3.85	14.91	0.29	0.19	0.19	1.50	0.50	0.10	3.06	-1.015	0.935	-0.498
4.65	17.32	0.21	0.26	0.09	1.21	0.39	0.26	3.61	-0.87	0.225	-0.131
5.15	18.82	0.00	0.31	0.19	1.10	0.20	0.19	2.70	-1.155	-0.382	0.068
5.65	19.96	0.50	0.35	0.31	1.55	0.48	0.16	4.39	-0.555	0.851	0.173
6.15	21.06	0.40	0.29	0.19	1.65	0.40	0.00	5.27	-0.592	0.953	-0.643
6.65	22.16	0.45	0.29	0.41	1.69	0.61	0.00	4.06	-0.935	1.62	-0.083
7.15	23.25	0.37	0.29	0.28	1.82	0.28	0.00	4.25	-0.518	0.576	-0.586
7.65	24.45	0.23	0.16	0.16	2.14	0.45	0.11	6.80	-0.226	1.486	-1.207
8.15	25.86	0.22	0.27	0.27	1.59	0.20	0.20	3.55	-0.473	-0.13	-0.249
8.65	27.27	0.60	0.28	0.47	1.54	0.33	0.19	3.40	-0.103	0.088	0.078
9.15	32	0.58	0.29	0.67	1.60	0.50	0.33	5.08	0.151	0.678	0.586
9.65	40.33	0.42	0.42	0.92	2.14	0.36	0.28	4.67	0.072	0.724	1.123
10.15	48.67	0.37	0.37	0.55	1.51	0.18	0.27	2.98	-0.251	-0.459	0.633
10.65	54.87	0.53	0.32	0.53	1.90	0.42	0.42	4.32	0.166	0.474	0.606
11.15	58.77	0.23	0.21	0.46	2.18	0.20	0.20	2.77	-0.259	0.195	-0.345
11.65	60.64	0.35	0.00	0.25	1.48	0.33	0.38	2.51	-0.05	-0.245	-0.823
12.15	62.39	0.44	0.19	0.25	1.48	0.44	0.21	3.27	-0.494	0.476	-0.347
12.65	64.14	0.65	0.19	0.40	1.53	0.37	0.14	3.81	-0.001	0.262	-0.461
13.15	65.89	0.73	0.33	0.36	2.16	0.73	0.20	3.27	-0.555	1.925	0.331
13.65	67.64	0.75	0.08	0.52	1.71	0.20	0.18	2.63	0.552	-0.478	-0.801
14.15	69.39	0.40	0.00	0.45	3.30	0.30	0.38	6.20	1.193	1.172	-1.481
14.65	71.17	0.64	0.00	0.35	2.07	0.22	0.27	12.09	2.118	0.435	-2.135
15.15	73.31	0.23	0.25	0.40	1.58	0.33	0.29	4.35	-0.327	0.246	0.029
15.65	75.46	0.51	0.19	0.55	1.05	0.34	0.16	1.76	-0.493	-0.295	0.097
16.15	77.6	0.23	·0.30	0.44	0.75	0.14	0.11	1.70	-0.94	-0.963	0.287
16.65	79.74	0.25	0.15	0.22	0.85	0.00	0.19	1.45	-0.476	-1.591	-0.586
17.15	83.42	0.43	0.22	0.68	1.10	0.19	0.13	2.94	-0.185	-0.632	0.082
17.65	87.28	0.25	0.26	0.62	1.68	0.55	0.20	3.91	-0.729	1.192	0.405
18.15	90.78	0.53	0.27	0.37	1.34	0.39	0.22	1.93	-0.578	0.06	0.234
18.65	94.3	0.70	0.30	0.43	0.82	0.28	0.51	1.81	0.082	-1.213	0.926
19.15	97.81	0.40	0.21	0.23	0.50	0.12	0.22	1.33	-0.602	-1.514	-0.101
19.65	101.31	0.25	0.19	0.35	1.25	0.19	0.19	2.13	-0.575	-0.554	0.268
20.15	104.82	0.30	0.32	0.42	0.72	0.25	0.28	1.34	-0.891	-0.873	0.753
20.65	109.85	0.13	0.21	0.36	0.32	0.17	0.19	0.77	-1.179	-1.315	0.228
21.15	117.34	0.33	0.53	0.62	0.85	0.38	0.32	2.48	-1.007	-0.221	1.867
21.65	122.71	0.24	0.32	0.33	0.42	0.08	0.09	1.00	-1.13	-1.43	0.298
22.15	124.57	0.16	0.19	0.23	0.45	0.00	0.10	1.36	-0.892	-1.692	-0.421
22.65	126.43	0.34	0.43	0.45	0.77	0.00	0.45	3.85	0.066	-1.786	1.014
23.15	128.23	0.61	0.59	0.50	1.87	0.41	0.22	6.35	-0.078	0.908	1.089
24.45	132.04	0.80	0.76	0.69	1.51	0.38	0.64	4.67	0.3	-0.208	2.887
24.95	133.51	0.24	0.05	0.36	2.00	0.29	0.14	5.93	0.181	0.632	-1.372
25.45	134.97	0.25	0.36	0.25	2.20	0.16	0.14	3.73	-0.418	0.281	-0.252
25.95	136.31	0.44	0.15	0.31	1.23	0.37	0.32	3.48	-0.166	-0.118	-0.261
26.45	137.66	0.83	0.60	0.60	1.04	0.25	0.35	3.50	0.056	-0.78	1.773

Appendix (continued).

MBSF	Ky	Smectite	Palygor	Illite	Quartz	Plagio	Chlorite	Dolomite	Factor 1	Factor 2	Factor 3
26.95	139	0.62	0.29	0.55	1.31	0.17	0.50	5.10	0.849	-0.983	0.484
27.45	140.34	0.55	0.19	0.52	2.57	0.38	0.45	5.29	0.805	0.77	-0.195
27.95	141.68	0.67	0.23	0.39	0.74	0.00	0.28	3.74	0.555	-1.847	-0.199
28.45	143.02	0.64	0.38	0.90	2.28	0.26	0.20	7.44	0.968	0.626	0.356
28.95	144.36	1.03	0.29	1.26	1.71	0.29	0.71	6.18	2.151	-0.752	1.511
29.45	145.71	0.65	0.12	0.31	1.47	0.31	0.31	5.59	0.659	-0.133	-0.774
29.95	147.11	1.53	0.32	1.13	1.34	0.00	0.55	8.68	3.324	-1.939	0.674
30.45	148.54	0.45	0.73	1.68	3.41	0.64	0.59	10.55	1.238	2.708	3.146
30.95	149.97	1.28	0.00	0.64	1.83	0.30	0.47	11.02	3.096	-0.179	-1.356
31.45	152.4	1.08	0.38	0.67	1.94	0.15	0.31	7.48	1.739	-0.402	0.134
31.95	157.4	1.24	0.43	1.16	2.73	0.46	0.41	7.46	1.956	1.055	1.135
32.45	162.4	0.00	0.00	0.44	1.24	0.41	0.30	4.19	-0.485	0.289	-0.651
32.95	167.4	0.41	0.00	0.50	1.09	0.44	0.41	1.78	-0.186	-0.268	-0.194
33.45	171.75	0.69	0.46	0.60	2.54	0.40	0.00	5.60	0.038	1.497	0.184
Repeat											
3.35	13.14	0.61	0.21	0.35	1.61	0.24	0.29	4.02			
12.65	64.14	0.28	0.34	0.48	1.22	0.18	0.43	2.53			
17.15	83.42	0.10	0.16	0.27	0.82	0.11	0.30	1.79			
21.65	122.71	0.36	0.39	0.43	0.87	0.23	0.09	1.37			
26.95	139	0.54	0.31	0.54	1.52	0.34	0.36	4.77			

Notes: "MBSF" is meters below sea floor; "Ky" is age ka; "Smectite", "Palygor", "Illite", "Quartz", "Plagio", "Chlorite", and "Dolomite" are mineral/boehmite peak area ratios for smectite, palygorskite, illite, quartz, plagioclase, chlorite, and dolomite respectively. "Repeat" denotes the repeated samples. "Factor 1", "Factor 2", and "Factor 3" are scores for each sample for the corresponding factor.